Correlation between oceanic environmental fluctuation and bluefin tuna behavior in the aquaculture pen

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ABSTRACT
The visceral temperature of three Pacific bluefin tuna cultured in the aquaculture pen were analyzed to estimate basal physiological condition. The data logger with depth and temperature sensor was surgically implanted in the abdominal cavity of the fish. The value of visceral temperature (T) was divided into 3 factors, which were the ambient water temperature (W), temperature fluctuation induce by swimming activity (S), and temperature fluctuation by food digestion and assimilation (F). In our analysis, S and F were estimated as follows; S = 1.3±0.33 ^{o}C, F = 0.8±0.85 ^{o}C. The elapsed times from digestion to assimilation were 38 - 41 hour.

KEYWORDS: **Pacific bluefin tuna, aquaculture, fasting visceral temperature, digestion, data logger**

INTRODUCTION

The body temperature fluctuation of Pacific bluefin tuna may provide us many fundamental physiological conditions and information about the growth process, which were difficult to be known in the natural environments. The data logger is a very powerful tool for physiological and behavioral studies. If we obtain the biological and physiological information of tuna in the net pen, we will be able to monitor their growing process as well as environmental fluctuation. For the purpose of understanding the behavior of the tuna in the net pen, the visceral temperature fluctuation was measured and analyzed.

MATERIALS AND METHODS

Background of analysis

Carey et al., (1984) suggested that the body temperature fluctuation of bluefin tuna consisted of three physiological factors. We tried to understand quantitatively 3 factors in detail. The visceral temperature fluctuation can be separated into three factors as shown in eq-1).

$$T(t) = W(t) + S(t) + F(t) \qquad 1),$$

where T(t) is the visceral temperature, S(t) is temperature fluctuation induced by swimming activity in the fasting phase, F(t) is temperature fluctuation induced by food digestion and assimilation, W(t) is the factor induced by water temperature fluctuation and t is time elapsed.

The schematized thermal regulation in the cavity is shown in Fig.1. The temperature fluctuation by swimming muscle is S(t), by digestive system such as stomach, intestine and caecum is included in F(t), the ambient water temperature fluctuation is W(t). Assuming that each fish swam at constant speed in the net pen, we can estimate S(t) from a data of T(t) and W(t) in the fasting period (F(t) = 0). The temperature fluctuation induced by swimming S(t) might be closely correlated with ambient water temperature fluctuation W(t) (Fig.2). Total time from ascending to descending was shown at about 36 to 48 hours, that is, a period from digestion to assimilation appeared to be about 40 hours at most.

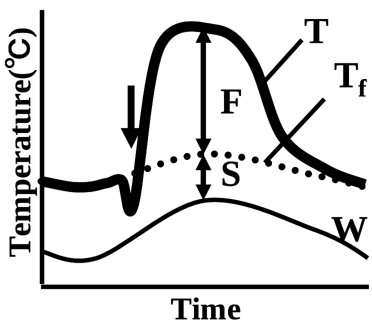

Fig.2. Schematic daily visceral temperature pattern and 3 factors (W, S, and F).

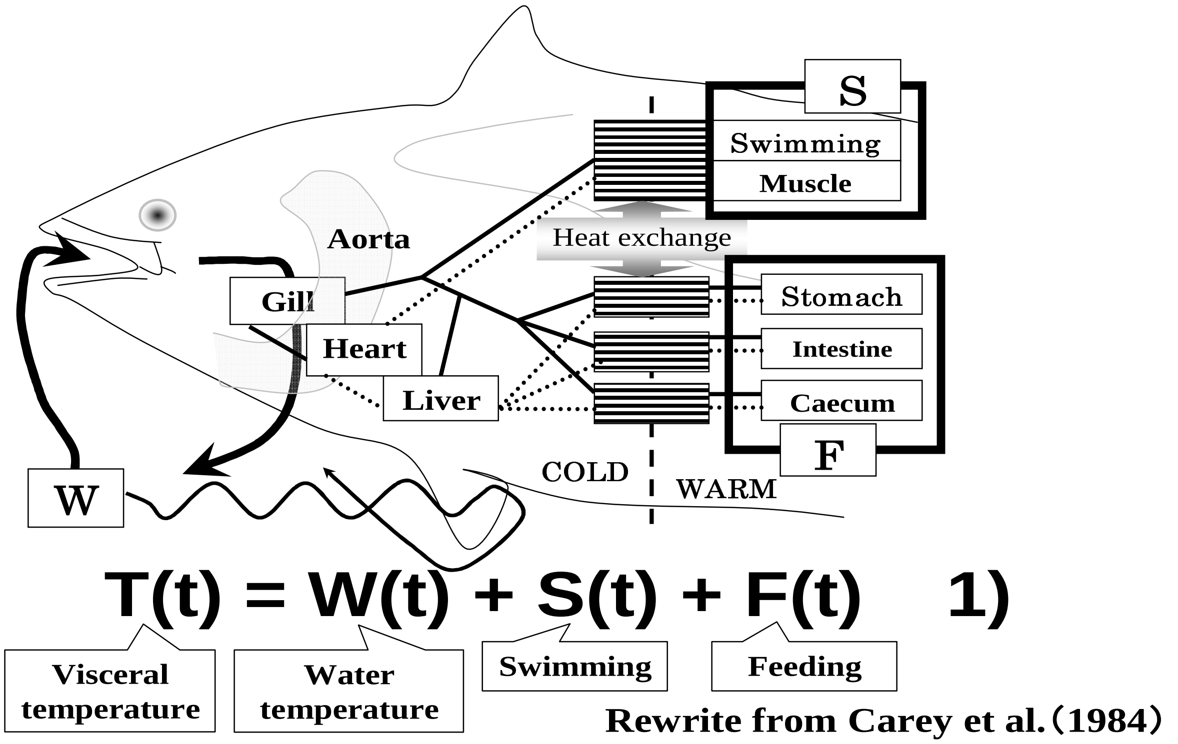

Fig.1. The thermoreguration system of a bluefin tuna, rewrite from Carey et al, (1984). The temperature fluctuation induced by swimming and muscle is S(t), stomach, intestine and caecum are in F(t), the ambient water temperature is W(t).

Measurement

In 2004, we began a series of experiments on cultivated 3 Pacific bluefin tunas (Fish No.1, 82 cm FL; No.2, 82 cm FL; No.3, 91 cm FL) attached with data loggers in Keten Bay, where is located southern part of Japan. Depth of the net pen is 20m. The visceral temperature was measured by a data logger which was surgically implanted in the cavity. The data logger records swimming depth and visceral temperature simultaneously every ten minutes. Water temperature was measured at three layers 1, 5, and 10 m in deep vertically with MDS-Ts (Alec Elec. Co., Kobe Japan) beside the net pen to refer to visceral temperature. MDS logger interval was ten minutes. The vertical water temperature profile in each time and depth was calculated from those three layers data, and ambient water temperature of the tuna was estimated from the vertical temperature profile referring to the swimming depth of each tuna in each time. We decided this estimated ambient water temperature as W(t).

From Monday to Saturday except Sunday, We fed mackerel to tuna at 9:00 and second feeding was 15:00.

RESULTS

The time-series data was obtained by bluefin tunas between 7th July and 7th September 2004. The time-series data of tuna No.1 is shown in Fig.3. The fluctuation in time series was divided into 3 typical phases. They were fasting phase (7th July-26th July), feeding phase (26th July-5th Sept) and typhoon landing phase (5th Sept-7th Sept). During the fasting phase, the visceral temperature of tuna remained relatively stable throughout 19-day periods. Perhaps fasting was caused by the stress of the surgical implantation inserting a data logger. However, visceral temperature was 0.1 to 3.1 ^{o}C higher than the ambient water temperature W(t) throughout fasting phase.

The stress driven by surgical implantation lasted for 19 days from the experiment beginning and tuna began to feed again on the 26th July. After the tuna began feeding, the visceral temperature elevated rapidly and gradually descended in accordance with feeding; At first visceral temperatures rise up quickly 2 to 3 ^{o}C within 1 hour after feeding, and last for 2 to 4 hours and after then, temperatures gradually descended until their value falls down to the initial basic condition before feeding. As the tuna were not fed on

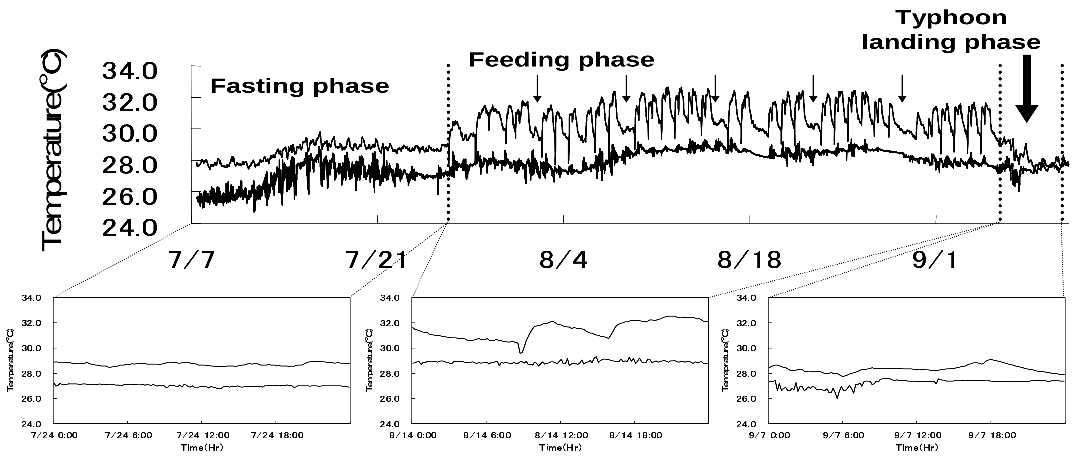

Fig.3. Upper: Time-series data recorded by Bluefin No.1 from 7th July to 7th Sept, Upper line is visceral temperature and lower line is ambient water temperature.
Lower: Enlarged typical time series shown in Fasting phase (7th July – 26th July), Feeding phase(26th July – 5th Sept), and approach of typhoon No.18 (5th Sept – 7th Sept)

Sundays throughout experimental periods, there were different periodical thermal fluctuations in every 6 day interval as shown arrows in Fig.3.

The temperature data did not show periodical feeding pattern at the end of experiment from 5th to 7th Sept, which was caused by the passage of typhoon No.18. The temperature fluctuation was similar to that during the fasting period. However visceral temperature during the typhoon passage was lower than that during fasting period even though the fish were under fasting condition in both periods. The tunas died on the 8th Sept.

Data analysis

Analysis of fluctuation in visceral temperature

Three cultivated tunas were used in the data logger experiment. Their temperature records in August were divided into two typical fluctuation patterns based on the feeding frequency as shown in Fig.4. The left hand side in Fig.4 shows the pattern when the tuna was fed once per day and right hand side shows twice feeding per day. Feeding time is indicated by thick arrows. The data during the fed once period was used to estimate the process of digestion to assimilation.

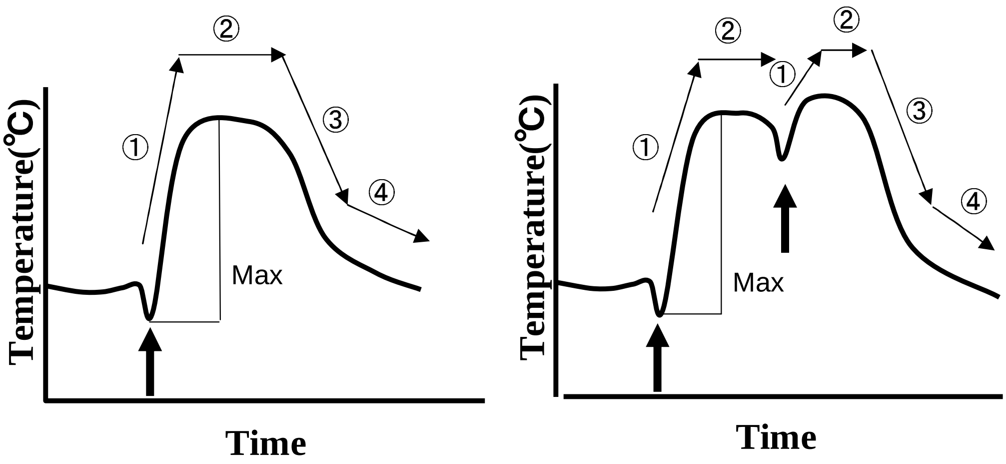

Fig.4. Two different schematic visceral temperature patterns shown in once feeding (left) and twice feeding (right) per day.

Furthermore we divided the fluctuation during the fed once period into 4 stages based on time and characteristic value of temperature fluctuation. The first stage (stage 1) is shown by the time, which is the time from the tuna taking food to reaching maximum temperature (Max). Stage 2 is the duration maintaining Max with high plateau, stage 3 is the duration from beginning to the ending of gradual descending, and final stage 4 is defined as the duration from the beginning of steady descending to the initial basic level. The stage 1 is the most drastic and interesting phase. From the data of stage 1, we estimated that the digestion lasted for 1 to 4 hours and their thermal gradients (^oC/time) are shown 0.322(R^2=0.7902), 0.0257(R^2=0.7784), and 0.0263(R^2=0.7977) . In the case of twice feeding, stage 1 and stage 2 are shown twice in accordance with the feeding time: 9:00 and 15:00. Stage 2 in the first feeding was interrupted and stage 1 of the new stage standard shown in Fig.4 (right). Similar pattern is shown in Fig.3 except the part indicating by arrows. Total time from ascending to descending was shown as about 38 to 41 hours, that is, a period from digestion to assimilation appeared to be about 40 hours at most.

Total 40 hours from digestion to assimilation is estimated by Figs.3 and 4. The process from digestion to assimilation is thought to be shown as the visceral temperature fluctuation from rapid ascending to gradual descending if the tuna was fed once per day. While if the tuna was fed twice per day, it may be hard to distinguish each process by use of time series visceral temperature fluctuation since the latter digestion process is overlapped on the process of the former assimilation.

Fasting visceral temperature

The correlation between water temperature W(t) and S(t) is calculated from the data in fasting phase and the duration between the second feeding period on Saturday and the first feeding on Monday, F(t) = 0. Fasting visceral temperature T_f is defined as eq-2)

$$T_f(t) = W(t) + S(t) \qquad 2),$$

Since the subtract T(t)－W(t) means S(t), S(t) of the three fish is calculated as follows

$S(t)=-0.250W(t)+8.471$(No.1, R^2=0.5752)

$S(t)=-0.340W(t)+10.455$(No.2, R^2 = 0.8073)

$S(t)=-0.275W(t)+8.841$(No.3, R^2 = 0.7390)

The linear correlation between subtract S(t) and W(t) is shown in Fig.5

From eq-2, we can estimate cavity temperature before feeding, in other words, before digestion and assimilation throughout the experiment (Fig.6). Figure 6 is the data obtained from No.1 tuna. The variation of T_f in the feeding period is similar to that in the fasting period. Basically the energy consumed by swimming seems to be independent to the environmental thermal fluctuation. Thermal fluctuation due to the feeding is clearly shown in Fig.6 during 14 and 20 August.

Finally, we can show the process of death of these fish. Typhoon No.18 came close to our net pen on the 5th Sept and stayed until 7th Sept. In Fig.7, we can show the visceral temperature (upper), water temperature (middle) and swimming depth of tuna during the passage of typhoon. Tuna continued normal feeding until 4th Sept, but they stopped feeding on 5th Sept as shown in in Fig.6 (upper). At the same time, water temperatures indicate reversed pattern, that is, the upper layer was cooler than the lower layer. Usually, water temperature in the upper layer is warmer than that in the lower layer since stable thermo-cline remains in the early autumn.

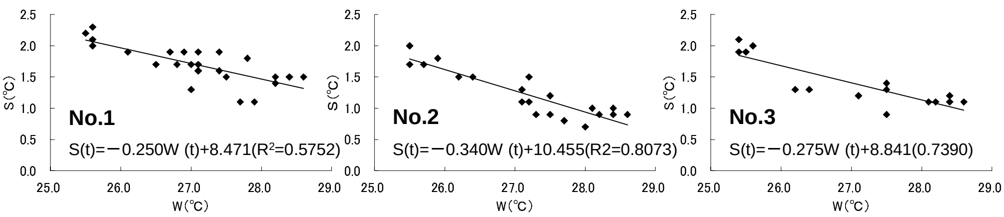

Fig.5. Relationship between remainder (visceral temperature T(t) － ambient water temperature W(t) = S(t)) and ambient water temperature. Left: No.1, middle: No.2, right: No.3.

Swimming depth was very restricted around 15m until the typhoon passed through as shown in Fig.6 (lower).
On the 7th Sept, the tuna migrated upward but soon sank down. They were cooped up in very narrow space around 15m (Fig.7). They died on 8th Sept.

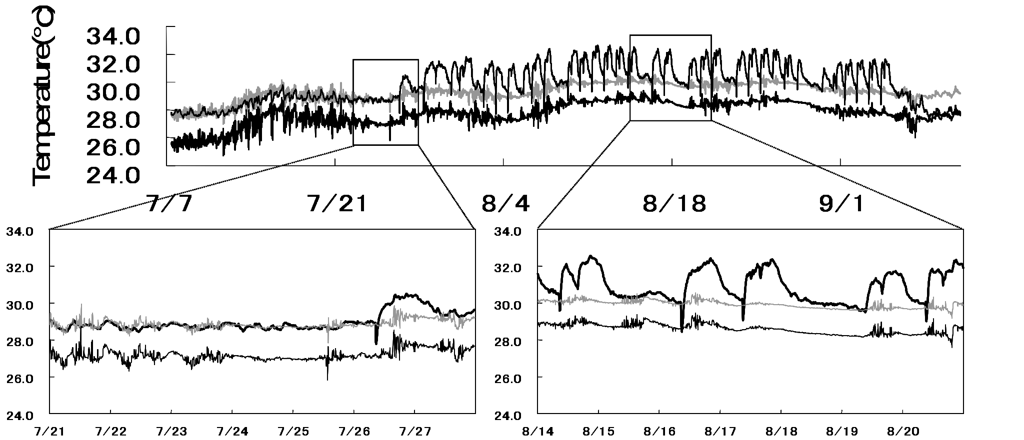

Fig.6. Temperature gluctuation of recorded visceral temperature, calculated value in fsting phase, and recorded ambient water temperature. Upper and lower graph: upper black line is visceral temperature T(t), gray line is fasting visceral temperature $T_f(t)$, lower black line is ambient water temperature W(t).

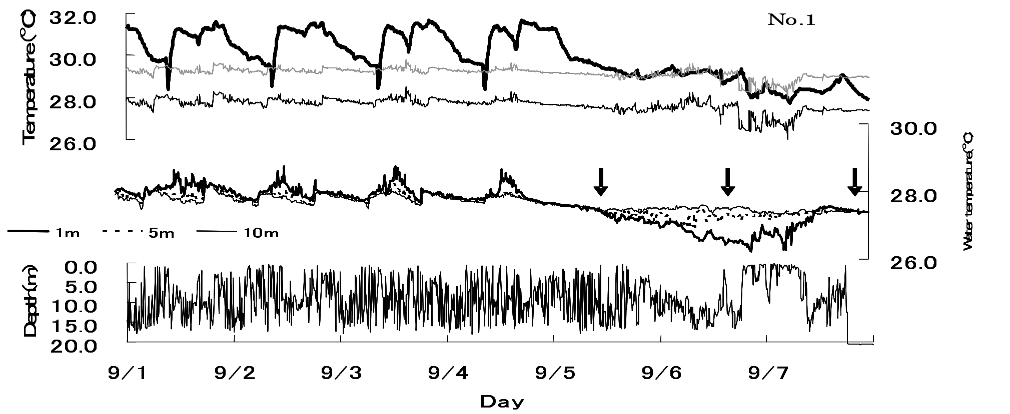

Fig.7. Upper figure: Time-series of recorded visceral temperature (upper, black), calculated Tf (middle, gray), and ambient water temperature (under, black).
Middle figure: Water temperature of 1, 5, and 10m.
Lower figure: Swimming depth of bluefin tuna.

DISCUSSION

The pattern of the visceral temperature

Carey et al. (1984) pointed out that the main origin of body heat were stomach and caeca during digestion. The highest temperature may be recorded at the end of digestion. The caeca are still in active condition at the time when the stomach stops digestion. We thought the ascending and descending process in visceral temperature was shown in stage 1 and 2 in Fig.4, and estimated that the stage 1 was heat generation period in the ascending process due to the digestion in stomach and caeca, the stage 2 was in the ascending process due to heat diffusion from caeca. Rapid descending in visceral temperature in stage 3 seemed to be caused by heat loss in internal organs as well as heat absorption in intestine. Finally stage 4 was gradual heat diffusion process from inside to out side of the body by organs such as retia, gill and fatty body skin. The final process might include the effect of excretion since fluctuation in cavity temperature in the final part was somewhat different from the other stage of digestion and assimilation.

Fasting visceral temperature

We defined the fasting visceral temperature (T_f) as the temperature in the fasting phase, and revealed the linear correlation between the fasting visceral temperature and ambient water temperature. The gradients of the linear correlation were different from each other tuna. The differences are probably influenced by the ability of thermal preservation in each tuna, such as the difference of body mass and surplus fatty contents. The T_f of bigger individual tended not to decline. Therefore, the big body mass has the advantage of the energy conservation.

The estimated value of the T_f is almost in accordance with the recorded value in the fasting phase (Fig.6). However, the estimated T_f included rapid ascending and descending fluctuation as noises, although recorded temperature in the fasting phase in Fig.6 did not indicate such a rapid fluctuation but smooth. The similar smooth visceral temperature change is shown the correlation between visceral temperature and ambient water temperature in Kitagawa et al, (2001), in which there were several time lags of fluctuation in visceral temperature to the ambient rapid temperature fluctuations. We thought that this time lag was caused by the function of retia, since retia had a roll in thermal buffer ability of bluefin tuna (Carey et al, 1973). Tunas were cooped up in very narrow space around 15m in depth, and they died (Fig.7).

During typhoon landing, the other environmental condition such as rough sea, turbulent current, low dissolved oxygen might be added and the oceanic environmental conditions caused the different stress for survival from temperature fluctuation. Environmental oceanographic condition suggests to us that there were two different fatal conditions. One was low salinity in upper water diluted by the heavy rain fall, another was bottom layer rough turbulent current induced by strong wind. Perhaps low salinity water in the surface layer was very turbid.

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